REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1996

3. REPORT TYPE AND DATES COVERED
Final Technical Report (1/94-12/95)

4. TITLE AND SUBTITLE
Three-dimensional Auditory Localization as a Cue for Spatial Orientation in Aircraft

5. FUNDING NUMBERS
G 549620-94-1-0114
Project Task 2313/CS
PR FQ8671-9400739

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8. PERFORMING ORGANIZATION REPORT NUMBER
TTU-IE-96-02

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Spatial Orientation Program
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

19960322 032

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The use of technology which provides spatially localizable auditory cues through headphones is proposed as a means of providing supplemental information to pilots on the spatial orientation of an aircraft. This technique shows promise for reducing accidents due to spatial disorientation associated with high visual load. An Auditory Head-up-Display (HUD) was developed that provides realtime aircraft pitch and roll indications in the form of spatially localized auditory tones. Three studies were conducted using U. S. Air Force pilots as subjects to determine its utility. The first study examined cue characteristics for optimizing vertical localization of auditory cues and successfully identified multi-dimensional cueing techniques that significantly improved localization performance. In the second study it was found that the addition of Auditory HUD information improved performance in a flight management task but not in a secondary visual search task. In the third study, the cues were employed in a recovery from unusual attitude task in a T-38 training simulator, however, no improvement in time to recover was found. Subjective data indicates that mentally processing the auditory cues is fairly demanding for subjects but was deemed useful. Implications for the use of three dimensional auditory cues in aircraft tasks and further research needs are discussed.

14. SUBJECT TERMS
Auditory Localization, Spatial Disorientation, Three-Dimensional Auditory Cues, Aircraft Attitude Displays

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

TTU-IE-96-02

THREE-DIMENSIONAL AUDITORY LOCALIZATION AS A CUE FOR SPATIAL ORIENTATION IN AIRCRAFT

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March 1996

Final Technial Report of Work Performed for
Project Grant #G 549620-94-0114
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INTRODUCTION

The loss of spatial orientation has plagued aviators since early flight experience in clouds and fog revealed that man's internal senses were not adapted for providing proper cues during the rapidly changing conditions associated with flight. Subsequent research has identified numerous disorientation conditions associated with a vestibular etiology, including somatogyral and somatogravic illusions which can produce false sensations of angular rotation and velocity in either the pitch, roll or yaw axes. In addition, disorientation has been linked to visual illusions including those associated with nystagmus, oculogyral illusions and oculogravic illusions among others (Benson & Burchard, 1973).

Despite diligent attention to training and the design of flight instruments, a fairly consistent number of accidents are attributed to spatial disorientation each year. In an analysis of accidents in the United States Air Force from 1954 to 1972, spatial disorientation was found to be a significant factor in between 4 and 6% of all accidents and between 10 and 26% of fatal accidents (Kirkham, Collins, Grape, Simpson, & Wallace, 1978). Between the years 1970 and 1980, approximately 17% of all cases of inflight incapacitation were attributed to spatial disorientation, of which 56% resulted in fatalities (Rayman & McNaughton, 1983).

The disorientation problem affects pilots across the aviation domain. Kirkham, et al (1978) found that while the incidence of spatial disorientation in general aviation accounts for only about 2.5% of all accidents, in 90% of these cases the accident involved fatalities, making it a factor in 16% of all fatal accidents. The problem is worse in high performance aircraft, however, both because disorienting maneuvers are easier to perform and because of a reduced recovery envelope associated with higher speeds. Sixty-eight percent of the spatial disorientation cases reported by Rayman and McNaughton (1983) involved fighter aircraft. McCarthy (1988) reports that two-thirds of all fatalities in the F-16 involve spatial disorientation as a causal factor. In a study involving 146 F-16 aviators in the Netherlands,

73% reported more disorientation in the F-16 than other aircraft (Kuipers, Kappers, van Holten, van Bergen, & Oosterveld, 1990).

Although these numbers may be somewhat inflated by a tendency for investigators to attribute accidents to spatial disorientation when no other cause can be found, they undoubtedly point to the presence of a problem worthy of attention. Particularly as Haber (1987) reports that the frequency of spatial disorientation related crashes does not appear to be diminishing, despite substantial investigative and training programs.

In light of this, new techniques for combating spatial disorientation need to be examined. Current programs focus on training aviators to maintain good instrument cross checks during flight as a means of combating the misleading visual and vestibular cues associated with spatial disorientation. While this method serves aviators well most of the time, it appears to be insufficient in certain circumstances. A high incidence of spatial disorientation has been found in high workload situations: Bombing over land or water, takeoff, intercept and approaches in clouds or at night (Rayman & McNaughton, 1983). In addition, Kuipers, et al (1990) found air combat, weather and formation flight to account for a high percentage of spatial disorientation cases.

A primary difficulty associated with instrument flight is that the central processing demands associated with instrument flight require a great deal of attention, particularly visual attention, of which pilots have a limited amount. Therefore, pilots must set up a scan pattern to insure that their knowledge does not get too out dated about any particular piece of information. These scan patterns can be highly disrupted by stressors or high workload, however, leading to attentional narrowing. Under high workload pilots may lose awareness of their spatial orientation as they are concentrating on other aspects of the situation that are monopolizing their limited attention.

Furthermore, other, possibly misleading information can be processed simultaneously with a high visual load. Out-the-window visuals involve the processing of global information and vestibular cues require processing involving other, non-visual

attention resources, both of which can be processed in parallel with visually demanding tasks. These cues (which may be perceived erroneously) may be quite accessible during high visual load, while instrument readings may be quite difficult. One therefore encounters an increased risk of spatial disorientation during stress or high workload, even with highly trained and experienced pilots.

To combat the limitations of current instruments for providing orientation information, a novel approach to this problem is being investigated. It involves an alternate means of providing spatial orientation information that does not rely on vision or visual central processing skills, as other types of information presentation will be more likely to allow for parallel processing during high visual workload (Wickens, 1992). Three-dimensional auditory cues may be useful for providing supplemental spatial information related to aircraft orientation. The multi-dimensionality of auditory information allows that a single, simple signal could communicate not only spatial information, but also distance information, and stimuli discrimination. In relation to the spatial orientation task, three-dimensional auditory cues could be used to present a signal coming from the same location in space as other aircraft or missiles, the ground, or tanker refueling cues, among other implementations.

The primary advantage of three-dimensional auditory cues is that this information can be used by the pilot without visual processing, thus it is fairly easily processed in parallel with other visually demanding tasks. Furthermore, the spatial auditory information presented is very directly represented. That is, there is a direct correspondence with the spatial information desired. The mental transformation or interpretation required is minimal. It is therefore a very promising technology for assisting spatial orientation in aircraft tasks.

The use of localized auditory cues for improving performance has been demonstrated. Research by Perrott (1988) found that visual search time was reduced in the presence of auditory directional information. Visual performance was found to improve by an average of 200 ms for targets in the periphery of the visual field.

While accuracy of localization is not as great as that with the visual system, it has been found that people can localize signals to within 1° to 5° in accuracy in the horizontal plane, with decreasing sensitivity at 90° azimuth (the sides of the head) under direct (non-computer generated) conditions (Calhoun, Valencia, & Furness, 1987; Durlach, 1991). Localization performance in the vertical plane seems to be somewhat poorer than in the horizontal plane (Calhoun, Janson, & Valencia, 1988), probably due to the lack of vertical separation between human ears.

Current technology provides for the production of externalized sound images that can be heard through headphones. This technology is "based on the use of digital filters that capture the magnitude and phase characteristics of the head-related transfer function (HRTF); the listener specific, direction dependent acoustic effects imposed on an incoming signal by the pinna" (Begault & Wenzel, 1993). This software has the ability to take into account individual differences in interaural amplitude, interaural phase & pinna cues to provide auditory cue localization (Wenzel, Wightman, & Foster, 1988). Wightman & Kistler (1989) investigated subjects listening performance under ordinary hearing conditions and with headphones using individualized HRTFs. These researchers found comparable localization accuracy between the two conditions. Since it is not always feasible to create individual HRTFs for each user, subjective localization performance with nonindividualized HRTFs is a critical issue in applied research (Begault, 1991).

Wenzel, Anuda, Kistler & Wightman (in press) conducted an experiment using broadband stimuli to test the use of nonindividualized HRTFs in headphone localization. Their results supported the claim that directional information for azimuth could be accurately obtained through nonindividualized HRTFs. A similar study by Begault & Wenzel (1993) however, did not find localization to be as accurate when the broadband signals used in the previous study were replaced by speech stimuli.

A particular aim of sound localization studies has been to relate aspects of localization behavior to particular spatial cues. The findings from these studies indicate that

horizontal localization relies on interaural difference cues and interaural delays and that vertical localization is dependent upon location specific transformations and spectral cues (Middlebrooks, 1992). Some investigators have also found spectral cues to aid in horizontal localization (Musicant & Butler, 1984). Furthermore, horizontal localization has been documented to be better in the frontal midline (0 degrees azimuth) than at the extremes (+/- 90 degrees azimuth) (Makous & Middlebrooks, 1990; Stevens & Newman, 1936; Strybel, Malingas, & Perrott, 1992). Begault and Wenzel (1993) found a mean average error of 28 degrees in horizontal localization and Wightman and Kistler (1989) found an average error of 20 degrees for subjects using their own HRTFs.

While most research in this area has focused on localization of sound cues in the horizontal plane, a few studies have investigated localization in the vertical direction. Makous and Middlebrooks (1990) found mean vertical localization errors of less than 10 degrees in the frontal midline (0 degrees) with a gradual increase in errors as azimuth increased. Strybel, Manligas and Perrott (1992) found vertical localization to be poorest at 80 degrees elevation. Earlier studies by Roffler and Butler (1967) suggested that for a stimulus to be accurately localized in the vertical dimension, the stimulus must have a broad bandwidth and contain high frequencies. These findings were further documented by Doll, Hanna and Russotti (1986). Butler (1986) found that as the bandwidth of stimulus decreased, the frequency of occurrence of front/back reversals increased. The more nearly sounds approach pure tones, the more inaccurate the localization regardless of absolute pitch. Middlebrooks (1992) found accurate localization to occur only when the auditory stimulus contained broad bandwidth and high energy frequencies.

The present research investigated the potential utility of three-dimensional auditory technology and examined methods for employing it to provide pilots with auditory cues on aircraft pitch and roll. This effort was conducted in a series of studies. The first sought to determine appropriate cue characteristics for presenting tones that need to be localized in both the horizontal and vertical dimension. The second study sought to examine the utility

of these cues when employed in conjunction with a typical flight task. The third study sought to examine their utility in aiding pilots in recovery from unusual attitudes.

STUDY ONE

The most direct spatial analog of aircraft pitch and roll involves changes in the vertical dimension corresponding to changes in the position of either the aircraft wing or nose. Insufficient data exists, however, regarding the best signal characteristics for optimizing human localization in the vertical dimension. It was the goal of the first study to determine auditory signal characteristics to utilize to improve vertical localization of a signal.

This objective was explored by examining the potential for augmenting the information provided purely by cue location with additional redundant cues. Specifically the use of a reference cue that is always presented at zero degrees in elevation was explored, as this may provide a baseline point to aid in locating a target cue which is presented at some location in space either above or below the reference point. In addition, a graduated condition was examined that provides a series of cues in five degree increments from zero degrees in elevation to the target cue location. The graduated cue provides additional information (number of cues) that may be used to improve vertical localization of the cue.

The type of auditory cue to provide was also examined. As a natural coding analog, successively higher tones may be associated with increases in the elevation of a cue and lower tones with decreases in the elevation of a cue. This variable tone condition was compared to a pure tone condition in which the frequency of the tone is held constant through all elevations. Although prior research shows that localization accuracy is best with broadband tones, a pure tone was included as a control condition against which the variable tone could be compared. To evaluate the potential for improvement in

performance over a pure tone due to the provision of multiple frequencies, an oscillating tone was also examined.

Little information exists regarding the frequency characteristics to use for achieving the best vertical localization accuracy. As previous research indicates that high frequency sounds are important, a high frequency cue was investigated that involved cues at 6000-7000 Hz. As this frequency is very high, however, and somewhat unpleasant, a low frequency cue (at 500-1500 Hz) was also examined. For an application in a cockpit environment, the comfort of the tone, the degree to which the tone distracts the pilot from other tasks, and the degree to which the tone is perceptible against the background of other audio cues are all important considerations that may outweigh purely technical considerations of localization accuracy. Subjective information was collected from the pilots who served as subjects as a first look at these implementation issues in relation to the different audio cues investigated.

Methodology

Experimental Design - A four factor experiment was performed. In addition to examining signal characteristics affecting localization (tone type, tone number and frequency type), two categories of pilot population were considered. The four independent variables were:

(1) Tone Type

(a) Pure - A single tone with a set frequency level at 6000 Hz for the high tone and 500 Hz for the low tone.

(b) Oscillating - A vibrating tone oscillating between 6000 Hz and 7000 Hz for the high tone and between 500 Hz and 1500 Hz for the low tone.

(c) Variable - A tone at zero degrees elevation was presented at 1000 Hz in the low tone or 5000 Hz in the high tone condition. Tones at higher elevations were presented with increasingly higher frequencies (+ 10 Hz/degree) and tones at lower elevations were presented with increasingly lower frequencies (-10

Hz/degree). Frequencies ranged from 100 Hz at -90 degrees to 1900 Hz at +90 degrees in the low tone condition and from 4100 Hz at -90 degrees to 5900 Hz at +90 degrees in the high tone condition.

(2) Tone Number

(a) Single - One tone was presented at the target azimuth and elevation.

(b) Reference - A pair of tones was presented in which the first tone was presented at 0 degrees elevation at the designated target azimuth. A second tone was presented at the target elevation and azimuth 750 ms later.

(c) Graduated - A tone was presented at 0 degrees elevation at the designated target azimuth and then succeeding tones were presented at the same azimuth at 5 degree intervals in elevation, until the target elevation was reached.

(3) Frequency Type

(a) High tone - (as specified in the tone type description)

(b) Low tone - (as specified in the tone type description)

(4) Subject Type

(a) Fighter Pilots (T-38 Instructors)

(b) Transport Pilots (T-1 Instructors)

All tones were presented for 900 ms in duration. All subjects were presented with all nine possible combinations of tone type and tone number. Conditions were administered in a random order. Frequency type was a between subjects variable. Half of the subjects participated in the low frequency condition (3 of each subject type) and half participated in the high frequency condition (3 of each subject type).

The dependent measures for each subject's performance were time to make a response and response accuracy. The response time was measured from the time the presented tone was completed until the subject responded with the complete azimuth and elevation of each tone. Response time for each trial was measured to the nearest hundredth of a second by the computer's clock.

Subjects - Twelve male pilots from Reese Air Force Base participated in this investigation on a strictly voluntary basis in accordance with the standards of the Human Subjects Use Committee at Texas Tech University. All subjects reported normal hearing. Pilot subjects' mean age was 28.25 years and mean years of flight experience was 8.29. Six subjects were T-1 Instructors (transport pilots) and six were T-38 Instructors (fighter pilots).

Task - Subjects were provided a brief description of the tone type and tone number combination and allowed one practice session (30 tone presentations) for each tone type/tone number combination. During the practice session, subjects were presented with an audio tone presented in the specified tone type/tone number condition and then received visual feedback on the tone's azimuth and elevation. Presentation of the tone and the visual feedback were subject paced.

Following each practice session, subjects were presented with a new set of 30 tones for the test session, and asked to verbally identify the azimuth and elevation of each tone as quickly and as accurately as possible. No feedback on the tone location or response accuracy was provided in the test condition. Following the practice session and test session for each tone type/tone number combination, a subjective questionnaire on that test condition was administered, following which the next condition was presented. Instructions, practice and testing for all nine conditions lasted approximately two hours. A short break was provided half way through the session. At the end of testing, subjects completed a subjective questionnaire on the use of this technology in aircraft applications.

Apparatus - The tones were generated through the Focal Point Three-Dimensional Audio System by Gehring Research on a 486 IBM compatible computer using a nonindividualized HRTF. Three tones were created using C++. Tone azimuths were evenly distributed at each of 5 azimuths (0, +/- 45, +/- 90 degrees). Tone elevations were randomly selected across 5 degree increments from +90 to -90 degrees. The order of

presentation of the 30 tone locations was randomized for each of the nine tone type/tone number conditions. Standard headphones were used to deliver the generated tones.

Results and Discussion

The data were analyzed as a 4 factor experiment: (1) Tone Type (pure, oscillating, variable); (2) Tone Number (single, reference, graduated); (3) Frequency Type (high, low); (4) Subject Type (transport/fighter). In addition, the effect of the location of the tones (azimuth and elevation) on subject performance was examined. The effect of each variable on subject response time, azimuth localization error and elevation localization error was examined. A total of 3240 targets were presented across the nine tone type/tone number combinations and the 12 subjects. Seventeen responses in which subjects changed their answers during their responses were omitted from analysis of response time.

Elevation Error - With respect to elevation localization accuracy, the variable/graduated tone condition turned out to be the best tone type/tone number condition, as shown in Figure 1, producing the least mean error in elevation, while the single/pure tone combination was the worst, closely followed by the oscillating/reference condition. The high tone reduced mean elevation error across all conditions, but particularly with the variable/graduated condition which reduced elevation error to a mean of 13 degrees.

Results of an ANOVA for absolute elevation error (Table 1) showed significant effects for tone type, F (2,3216) =66.35, $p < 0.001$, tone number, F (2,3216) = 37.78, $p < 0.001$, and frequency type, F (1,3216) = 26.11, $p < 0.001$. Significant interaction effects were present between tone type and tone number, F (4,3216) =5.85, $p < 0.001$, and between pitch and tone type, F (2,3216) = 11.84, $p < 0.001$. A significant three way interaction effect was found for frequency type by tone type by tone number, F(4,3216)= 3.55, $p<0.007$.

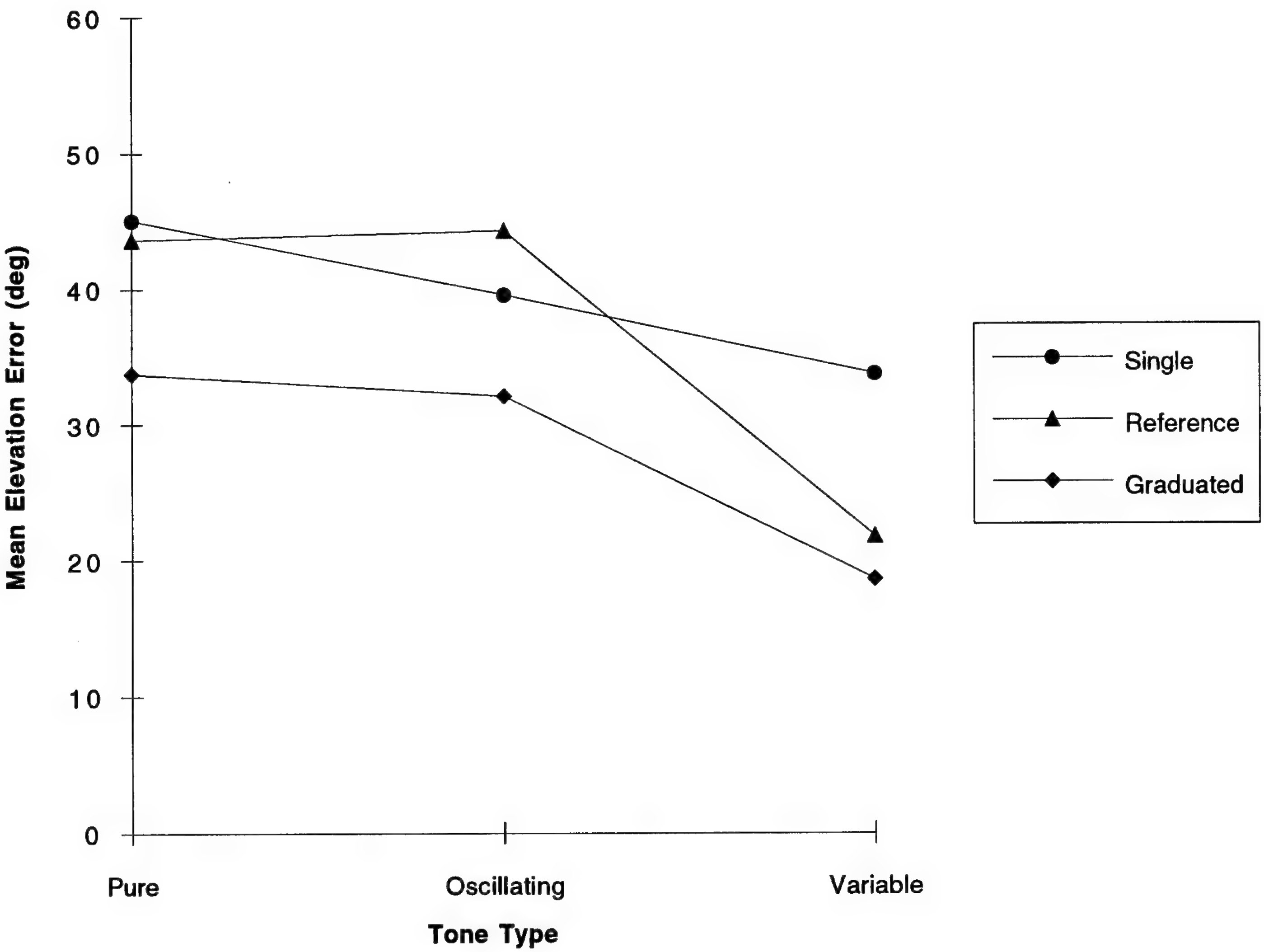

Figure 1. Mean elevation error for tone type by tone number

Table 1. Analysis of Variance: Absolute Elevation Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	155577.27	2	77788.63	66.35	0.000
Tone Number	88599.54	2	44299.77	37.78	0.000
Frequency Type	30613.33	1	30613.33	26.11	0.000
Subject Type	192.27	1	192.27	0.16	0.686
Tone Type * Tone Number	27478.20	4	6869.55	5.85	0.000
Frequency Type * Tone Type	27769.38	2	13884.69	11.84	0.000
Frequency Type * Tone Number	4326.13	2	2163.06	1.84	0.158
Frequency Type *Tone Type *Tone Number	16650.92	4	4162.73	3.55	0.007
Target Azimuth	95019.05	4	23754.76	20.26	0.000
Target Elevation	9274.05	1	9274.05	7.91	0.005
Error	3770369.37	3216	1172.37		

The least mean elevation error occurred in the variable tone condition (25 degrees) followed by the oscillating tone condition (38 degrees) and the pure tone condition (40 degrees). Across tone number conditions, the least mean elevation error occurred in the graduated condition (27 degrees) followed by the reference condition (37 degrees) and the single tone condition (39 degrees). The least mean error in elevation occurred in the high frequency condition (31 degrees) in comparison to the low frequency condition (37 degrees).

Figure 1 shows the least mean error in elevation occurred within the graduated condition followed by the reference condition overall, however, this was not true for the oscillating tone type. The combination of an oscillating tone with a reference cue produced

a greater amount of error, while the reference cue provided significantly better elevation accuracy in the variable condition. The variable tone was better for both the high and low frequency conditions, but much better for the high frequency condition with a mean error of 17 degrees, providing a significant interaction effect.

Overall, a 370% improvement was achieved through the addition of multidimensional cues for localization. The use of a graduated presentation of tones, providing a cue regarding the distance of the target from 0 degrees elevation, and a variable tone, providing a frequency change corresponding with elevation, provided extra, redundant cues that the subjects were able to use to significantly bolster localization over presentation of a single/pure tone.

Elevation localization accuracy was also significantly impacted by the azimuth and elevation of the presented cue. The ANOVA showed significant effects for target azimuth $\underline{F}$ (4,3216) =20.26, $\underline{p} < 0.001$ and target elevation $\underline{F}$ (1, 3216) = 7.91, $\underline{p} < 0.005$, Figures 2 and 3. Mean elevation error was best for targets presented in the right ear (+ 90 degrees azimuth) and worst for targets presented in the left ear (-90 degrees azimuth), with accuracy in between at 0 degrees and +/- 45 degrees azimuth. Mean elevation error appeared to be least for targets presented at 0 degrees elevation and in the upper quadrant up to +70 degrees elevation. Accuracy became dramatically worse at elevations below zero degrees (lower quadrant) and at azimuths above 70 degrees (near over head).

In regard to the effect of target location on localization accuracy, previous studies had indicated that localization performance is better in some areas than others. Vertical localization tends to be best near the horizon with errors increasing or decreasing with higher or lower elevations. In this study, elevation error was least in the upper front quadrant, with the greatest problems occurring at the extremes (head and feet regions). This finding agrees with previous studies. Elevation accuracy was also better on the subjects' right than on their left. This may indicate a right-ear bias or may indicate unequal hearing between the two ears on some subjects, even though all subjects reported normal hearing.

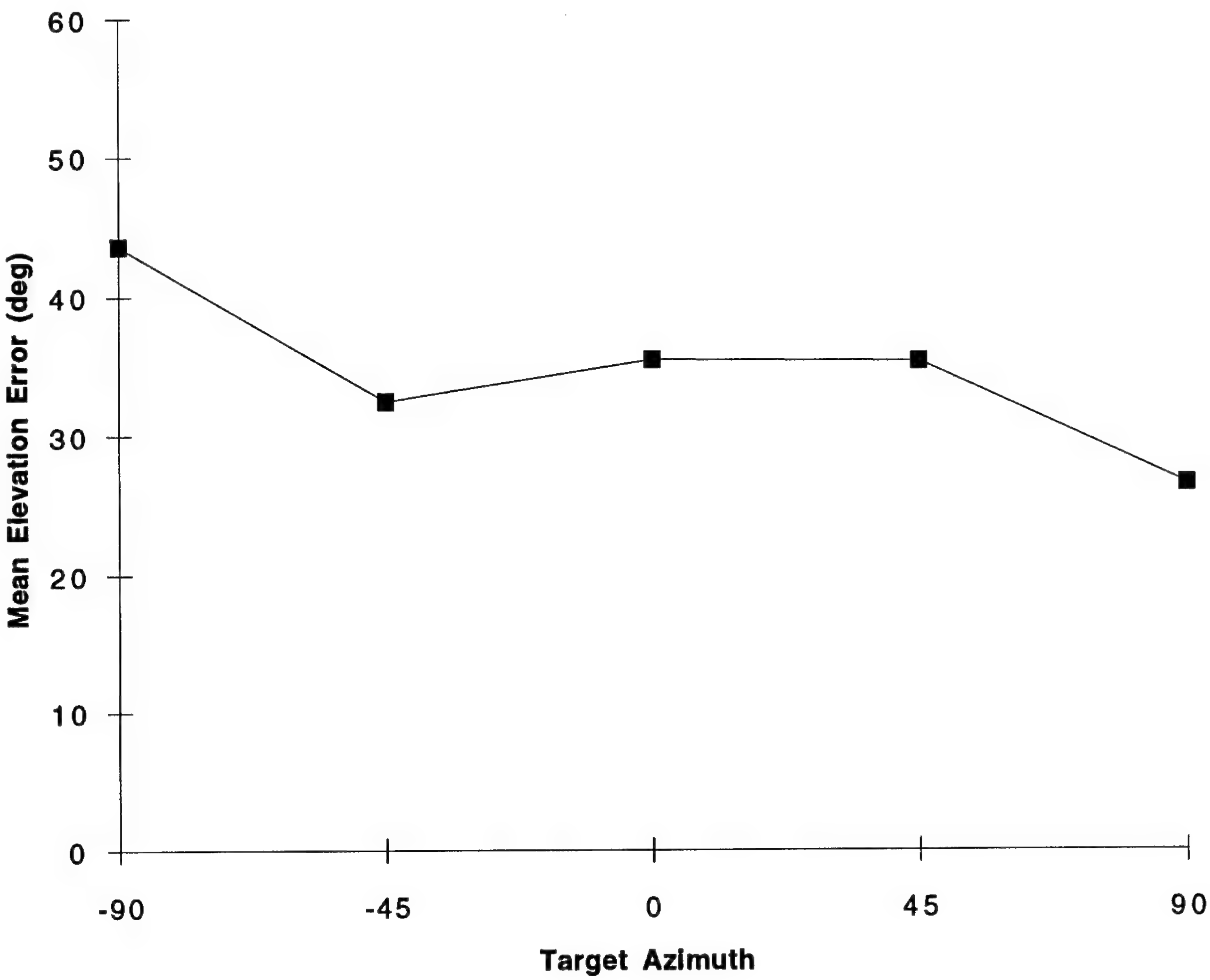

Figure 2. Mean elevation error by target azimuth

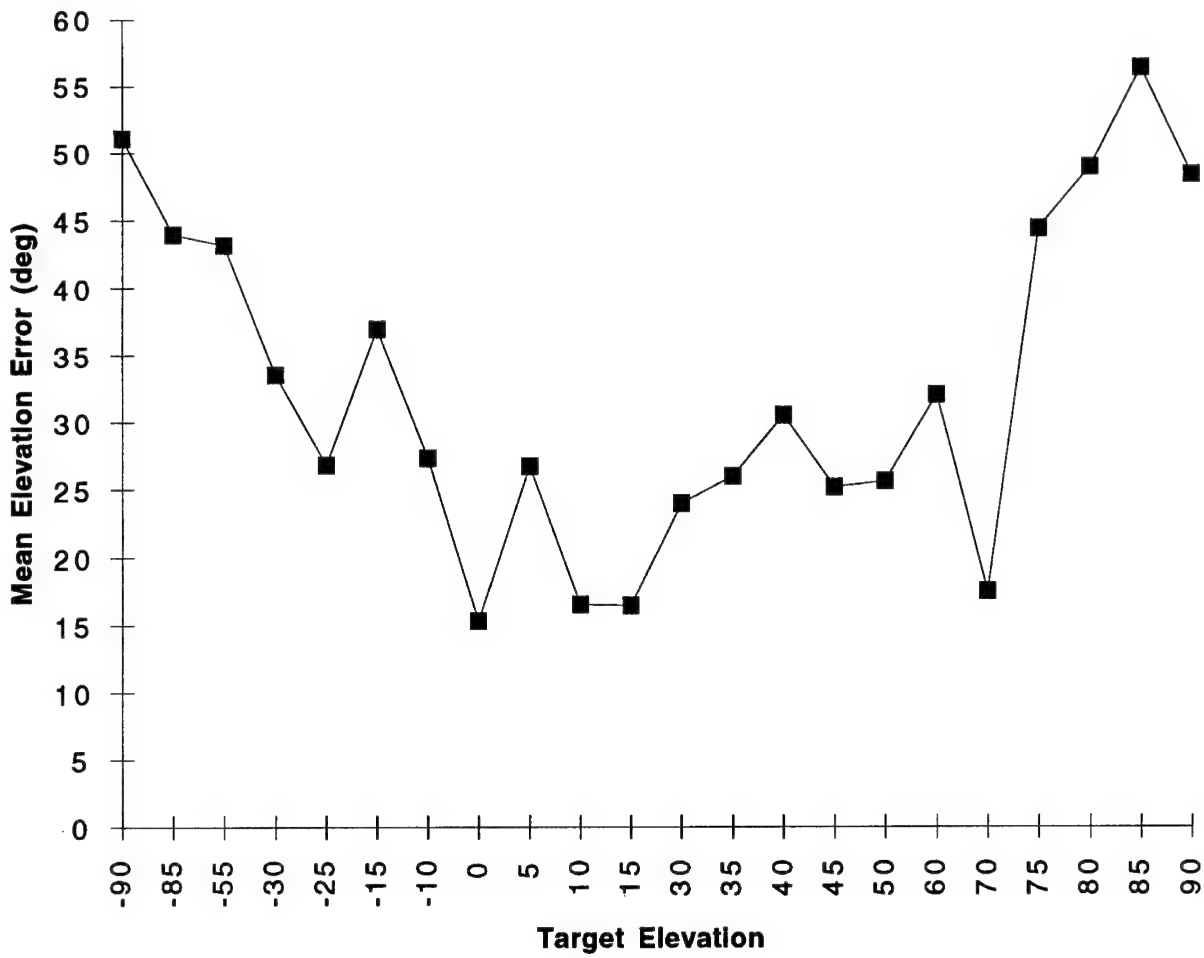

Figure 3. Mean elevation error by target elevation

Azimuth Error - Although the variable/graduated cue significantly improved accuracy in elevation judgments, it did not produce the best horizontal localization error. Overall, the oscillating tone produced a lower mean azimuth error than either pure or variable tones. The reference tone also showed a lower mean azimuth error than the graduated tone or single tone across all tone types. The variable and graduated cues were better than a single/pure tone, however. As with elevation error, the pure/single tone condition produced the most mean azimuth error (27 degrees), particularly with the low tone (33 degrees). It may be that while the variable and graduated cues significantly helped with elevation localization, they interfered with subjects horizontal localization of the cue.

The use of a high tone over a low tone also slightly improved accuracy of azimuth localization across most tone type/tone number conditions, except for in the variable and graduated conditions. As these produced the best elevation localization accuracy, this supports the view that interference with azimuth localization may have occurred.

Results of an ANOVA for absolute azimuth error (Table 2) showed significant effects for tone type $F\ (2,10) = 13.22$, $p < 0.001$, tone number $F\ (2,10) = 20.69$, $p < 0.001$, and for pilot type, $F(1,3216)=4.95$, $p<0.026$. Significant interaction effects were found for frequency type by tone type, $F(2,3216)=3.74$, $p<0.024$ and for frequency type by tone number, $F\ (2,3216)=3.15$, $p<0.043$. The analysis showed a significant three way interaction effect for frequency type by tone type by tone number, $F(4,3216)=2.55$, $p<0.037$.

Oscillating tone type had the least mean error in azimuth (16 degrees) followed by the variable tone type (21 degrees) and the pure tone type (24 degrees). The reference tone number had the least mean error in azimuth (17 degrees) followed by the graduated tone number (20 degrees) and the single tone number (24 degrees). The fighter pilot subjects had a lower mean azimuth error (19 degrees) than the transport pilot subjects (22 degrees).

Table 2. Analysis of Variance: Absolute Azimuth Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	22926.03	2	11463.01	13.22	0.000
Tone Number	35877.75	2	17938.87	20.69	0.000
Frequency Type	2264.32	1	2264.32	2.61	0.106
Subject Type	4290.84	1	4290.84	4.95	0.026
Tone Type * Tone Number	1840.85	4	460.21	5.31	0.713
Frequency Type * Tone Type	6493.41	2	3246.70	3.74	0.024
Frequency Type *Tone Number	5464.00	2	2732.00	3.15	0.043
Frequency *Tone Type *Tone Number	8847.35	4	2211.83	2.55	0.037
Target Azimuth	182549.26	4	45637.31	52.64	0.000
Target Elevation	96.91	1	96.91	0.11	0.738
Error	2787998.35	3216	866.91		

The frequency type by tone type interaction indicated that the least mean error in azimuth occurred in the high frequency condition for the pure and the oscillating tone types but not for the variable tone type. The frequency type by tone number interaction indicated the single and reference tone numbers were best under the high frequency condition but not the graduated tone number.

In general, then, it appears that the oscillating and reference cues significantly supported azimuth location judgments as compared to the single/pure tone condition. While the variable and graduated cues also improved azimuth accuracy, it was not to as great a

degree, possibly due to a predominance of vertical location information in these cues that distracted from the azimuth judgment.

Horizontal localization accuracy was also impacted by the azimuth of the presented cues. The ANOVA also showed a significant effect for target azimuth $\underline{F}$ (4,20) = 52.64, $\underline{p}$ < 0.001 but not for target elevation. Mean azimuth error was lowest at 0 degrees azimuth (directly in front), as shown in Figure 4, followed by tones at +/- 90 degrees azimuth (to the subject's right or left). Azimuth error was worst for targets presented at +/- 45 degrees. Previous studies have found poorer azimuth localization at the areas near the ears (+/- 90 degrees), and have found better performance directly in front (0 degrees). While this study generally agrees with these findings, it is not clear why such poor performance occurred at azimuths of 45 degrees.

Response Time - An examination of the response time data, Figure 5, shows that definite tradeoffs in time and accuracy were occurring across the experimental conditions. Response to the graduated tones (3.8 s) and single tones (3.7 s) was slower than to the reference tones (2.3 s). While the addition of a graduated tone cue significantly improved elevation localization accuracy, response time increased by 65 % when compared to the reference tone condition, and there was a small decrease in azimuth accuracy. It appeared to be taking subjects more time to process the additional information provided by this cue.

The variable cue slightly improved mean response time (3.2 s) over the oscillating (3.3 s) and pure tone conditions (3.4 s). The use of the variable frequency cue slightly improved response time simultaneously with large improvements in elevation accuracy, while azimuth accuracy was only slightly reduced.

Results of an ANOVA for response time (Table 3) showed tone type to be marginally significant $\underline{F}(2,3199)=2.83$, $\underline{p}<0.059$. Significant effects were found for tone number, $\underline{F}$ (2,3199)= 188.85, $\underline{p}<0.001$, frequency type, $\underline{F}$ (1,3199)=10.43, $\underline{p}<0.001$ and

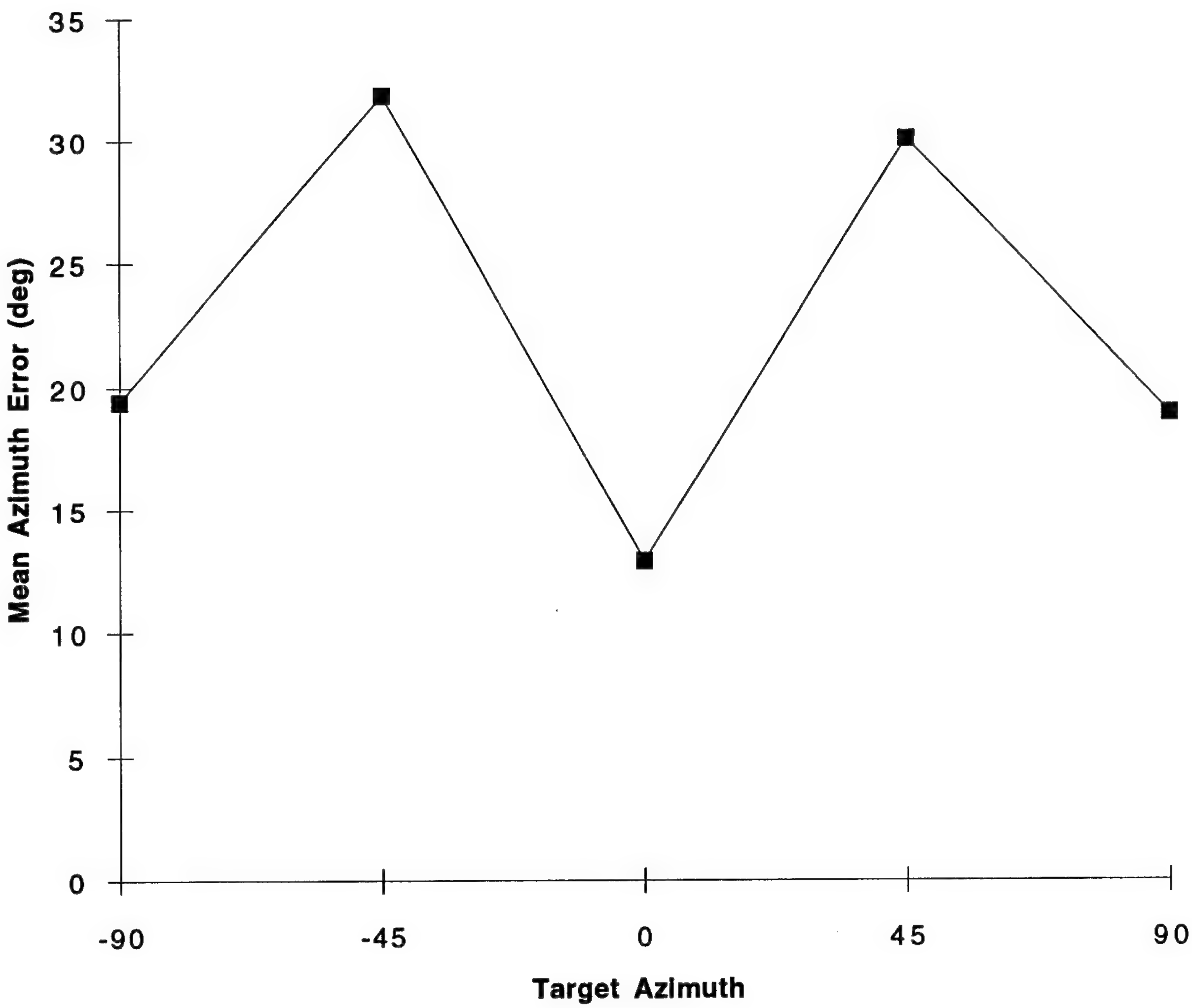

Figure 4. Mean azimuth error by target azimuth

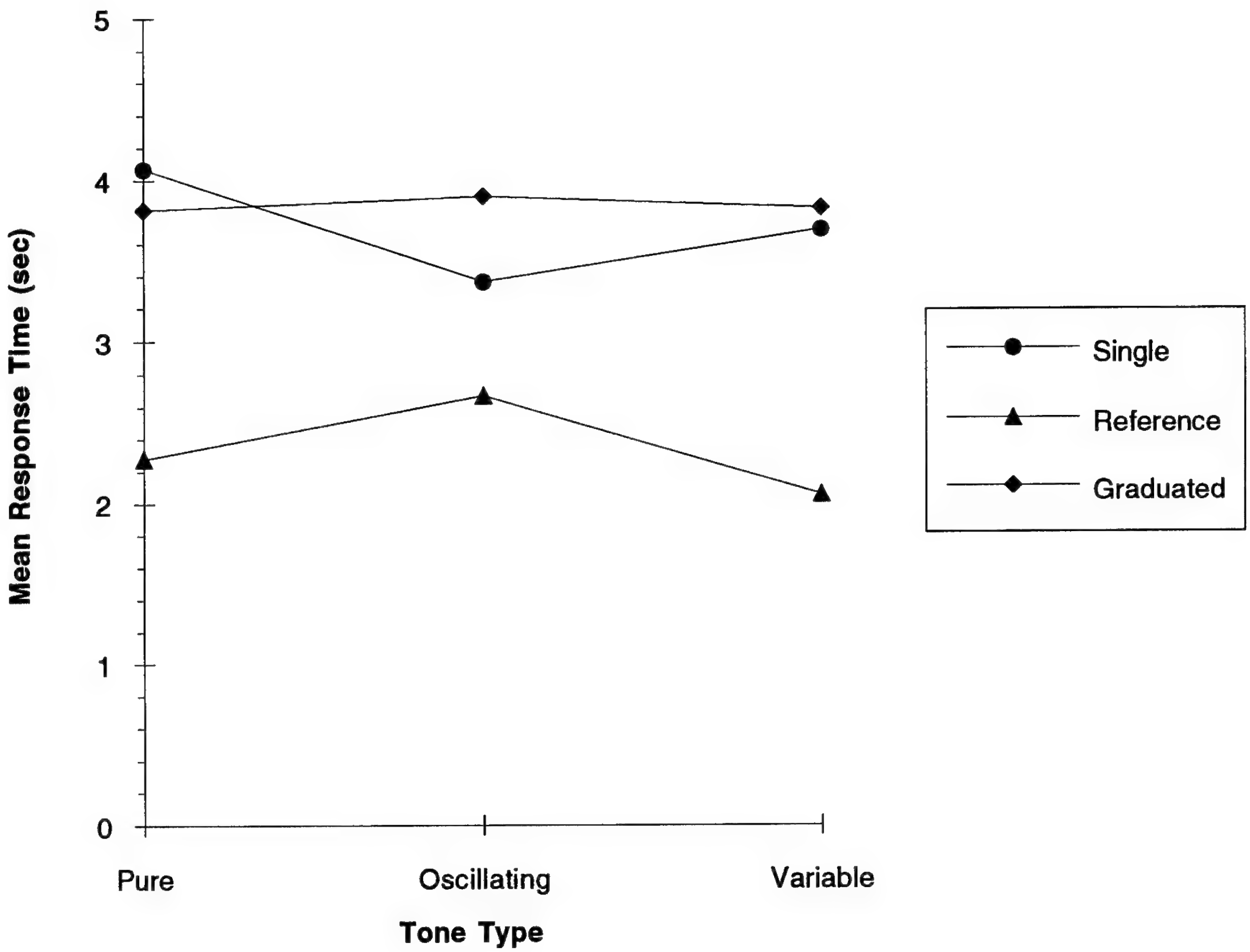

Figure 5. Mean response time for tone type by tone number

subject type, F (1,3199) = 152.94,p<0.001. Significant interaction effects were found between tone type and tone number, F(4,3199)=35.55, p<0.001, frequency type and tone type, F(2,3199)=6.76, p<0.001, and between frequency type and tone number, F(2,3199)=7.86, p<0.001. The three way interaction between frequency type, tone type and tone number was not significant.

Table 3. Analysis of Variance: Response Time

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	22.39	2	11.19	2.83	0.059
Tone Number	1491.77	2	745.88	188.85	0.000
Frequency Type	41.20	1	41.20	10.43	0.001
Subject Type	604.02	1	604.02	152.94	0.000
Tone Type * Tone Number	142.23	4	35.55	9.00	0.000
Frequency Type * Tone Type	53.45	2	26.72	6.76	0.001
Frequency Type *Tone Number	62.12	2	31.06	7.86	0.000
Frequency *Tone Type *Tone Number	11.75	4	2.93	0.74	0.562
Target Azimuth	53.98	4	13.49	3.41	0.000
Target Elevation	0.14	1	0.14	0.38	0.846
Error		12634.27	3199	3.94	

In addition to performing faster with the variable cue over the oscillating cue and the pure tone cue, and with the reference cue over the single tone and the graduated tone condition, mean response was quicker with the low frequency (3.1 s) when compared to

the high frequency (3.4 s). Transport pilot subjects (2.8 s) were also faster than fighter pilot subjects (3.7 s) in their responses.

The interaction between tone type and tone number reveals that the better response time for the reference condition was exaggerated in the variable tone type condition. The better overall mean response time for the oscillating tone as compared to the pure tone appears to be due primarily to the single tone condition. In the reference and graduated conditions, the oscillating tone did not provide faster performance.

Mean response time was quickest in the low frequency condition for both the variable (2.9 s) and oscillating (3.1 s) conditions but not for the pure tone condition (3.4 s), explaining the frequency by tone type interaction. In the pure tone condition the high frequency resulted in a slightly faster response time, while the low frequency condition had a quicker response time overall. The frequency by tone number interaction reveals that the difference between the low frequency and high frequency was greatest in the graduated condition, however, this was not the case for the single cue where the high frequency was slightly better (3.8 s).

The ANOVA for target azimuth was also significant $F(4,3199)=3.41$, $p<0.009$, while a regression on target elevation was not significant. Mean response time decreased slightly from -90 degrees azimuth (subject's far left) to 0 degree azimuth (directly in front) to a plateau at +90 degrees (subject's far right), showing a right ear bias similar to that found for elevation accuracy.

Subjective Responses - Chi-square tests were performed on subjective opinions regarding the tones presented. Subjects responded to questions with scaled, 5-pt anchored responses on the ease of localization (1-very difficult to 5-very easy), comfort of the tone (1-very uncomfortable to 5-very comfortable) and need for further training (1-not at all to 5-very much). Subjective ratings generally support the findings of the objective performance data in terms of a preference for the variable and graduated cues, although subjects also reported a greater need for training with these cues.

Figure 6 shows subjects rated the variable tone type presentation as slightly easier to localize than the oscillating and pure tone conditions, although this was not significant at the p=.05 level, nor was comfort level significantly different across tone type conditions. Subjective ratings indicated that subjects felt their performance in the variable condition was most likely to improve with increased training, $\chi^2 = 7.46$ (df = 2), $p<.05$.

Figure 7 shows that subjects rated the single tone as more difficult to localize, although this was not significant at the p=.05 level. The graduated tone was rated as the most comfortable to attend to (although this difference also was not significant) and was rated as most likely to improve with training, $\chi^2 = 9.49$ (df=2), $p<.05$. Mean ratings regarding the high and low tones were comparative in terms of the need for training with these cues. Subjects were more likely to report that localization was easier with the low cue than the high cue, $\chi^2 = 6.28$ (df = 2), $p<.05$, and to report that the low cue was more comfortable than the high cue, $\chi^2 = 23.7$ (df = 2), $p<.05$. So, although performance tended to be slightly better with the high cue, subjectively the low cue was preferred.

Conclusions and Recommendations

Localization performance in this study is comparable to accuracy noted in previous studies. Begault and Wenzel (13) found mean elevation accuracy of 28 degrees using synthesized speech. In this study, while the use of a single/pure tone produced rather poor elevation accuracy, the addition of graduated and variable cues produced much better results than those previously found for elevation judgments.

It can be concluded that the use of multidimensional cues appears to improve elevation localization which is normally rather poor due to the lack of vertical displacement in the ears. Further investigation of the use of variable and graduated cues to aid in localization accuracy is warranted. While these cues were advantageous in elevation localization, tradeoffs with azimuth localization and response time need to be examined. Increased training and experience with these types of cues is recommended to examine whether response time can be reduced to acceptable levels. Tradeoffs between elevation

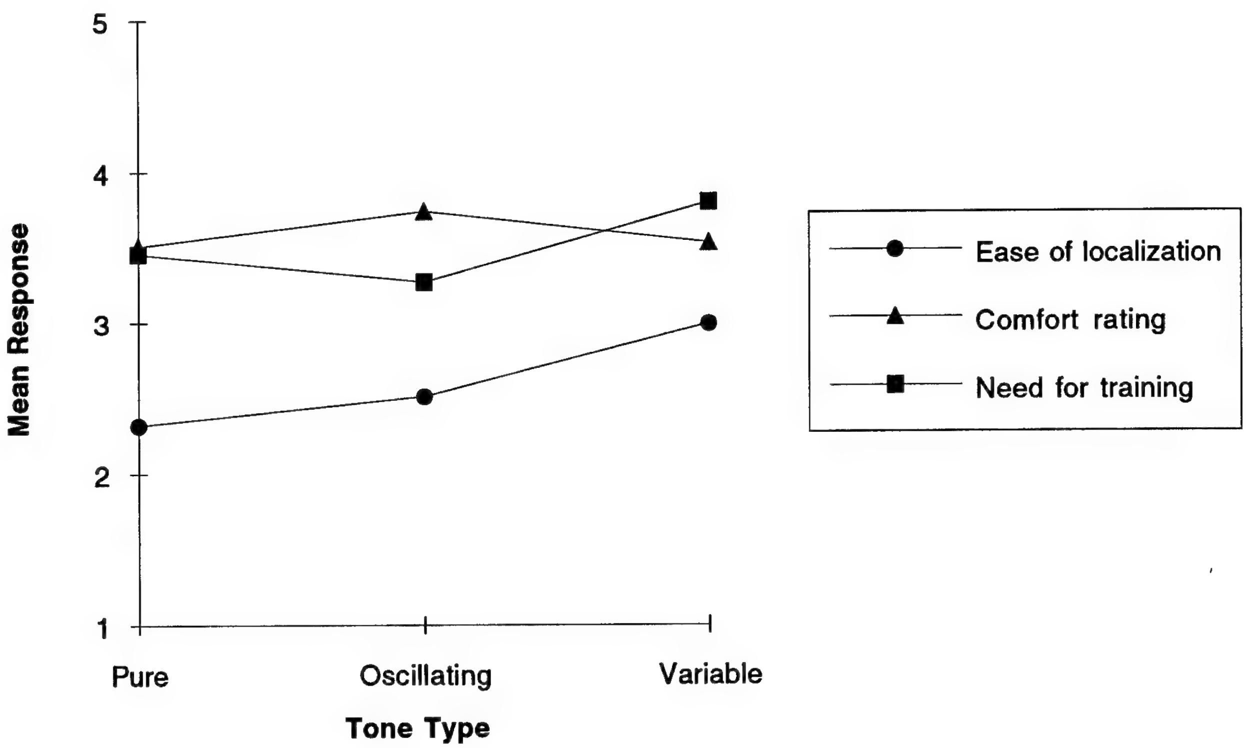

Figure 6. Mean rating across tone type

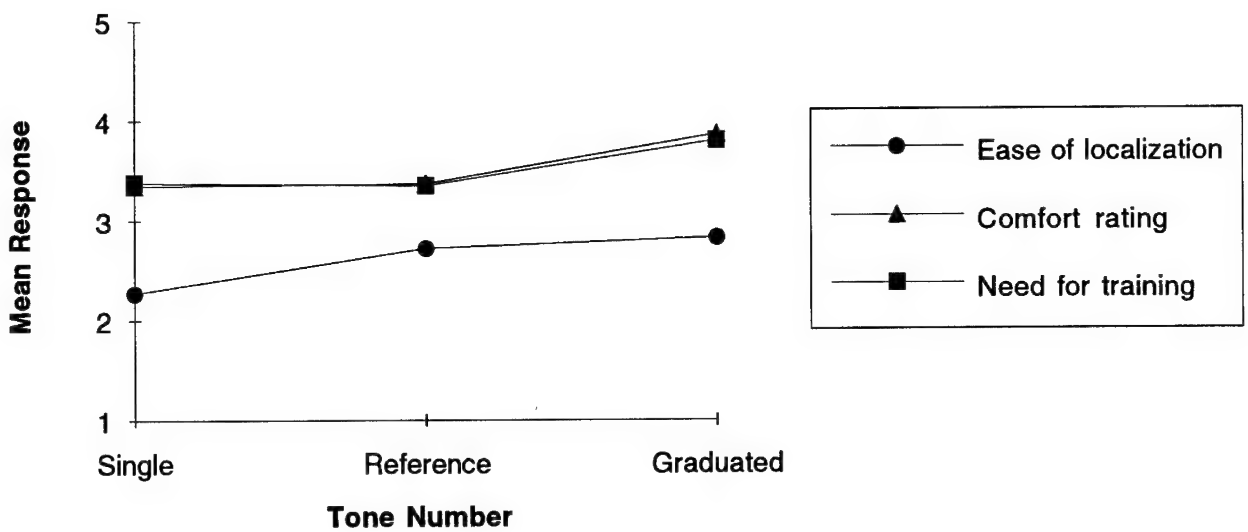

Figure 7. Mean rating across tone number

and azimuth localization also need to be examined more carefully. If cue characteristics that simultaneously improve performance in both dimensions cannot be found, the selection of cue characteristics may need to depend on which dimension is most important to the subjects' task.

The pilots who served as subjects in this task reported that they felt the three-dimensional auditory technique had merit for providing information in the cockpit. The way it should be implemented and integrated with flight tasks was of significant concern, however. The majority of the pilots were in favor of using such cues intermittently at pilot command, while performing certain tasks, or when the aircraft automatically detected a disorienting maneuver. They were concerned that the cues would be too distracting if presented all the time.

In the present study, discrete, static cues were presented under controlled laboratory conditions. Future research needs to examine the effectiveness of these multi-dimensional cues in a dynamic environment, where the relevant information portrayed by the cue (aircraft pitch and roll) is changing frequently. There may be a need to minimize the complexity of the presented cue in this situation. Other significant issues that need to be explored include a determination of the degree to which spatial auditory cues may provide correct sensory information in the face of conflicting vestibular or visual information under spatial disorientation, and the selection of a cue that is distinguishable from other audio cues and background noise in the cockpit. It is necessary to establish that localized auditory cues for orientation information can be effectively utilized by pilots within the specific conditions of flight and in conjunction with other flight tasks.

Overall, this study demonstrated that localization performance can be improved through the use of multidimensional cues. The use of these cues for providing spatial information regarding aircraft attitude appears to be feasible, and should be investigated further within that context.

STUDY TWO

The objective of the second study was to expand upon the first study by employing the three dimensional auditory cues in conjunction with simulated flight tasks to see whether an advantage could be found with their use. To this end, a display which provided a real-time auditory indication of aircraft pitch and roll in the form of a single localizable tone was needed. An Auditory Head-up-Display (HUD) was created for this purpose. There has been some precedent for this concept.

Work on an auditory Flybar Display was conducted during the second world war (DeFlores, 1936; Forbes, 1946). The Flybar used three tone presented at different frequencies in each ear to indicate airspeed (which varied as a function of pitch), bank angle and rate of turn. While pilots could fly with this auditory display, it was found that pilots had difficulty in attending to so many cues successfully. A second attempt combined the information into a single tone that was presented with changing relative intensity between the two ears, producing an illusion of motion that was mapped to the aircraft's turn rate, and changing relative frequency between the two ears that was mapped to bank angle. The rate of presentation of the signal indicated aircraft airspeed. Studies showed that this signal could be used to fly a course successfully, demonstrating the feasibility of the auditory display, however, more research on cue presentation was considered warranted.

More recently, Lyons, et. al. (1990) developed an Acoustic Orientation Instrument (AOI) which presents information on aircraft bank, vertical velocity, and altitude, and angle of attack. Neubauer, et. al. (1992) tested the AOI, which was restricted to present only bank angle through intensity differences between signals presented in each ear (up to a maximum of 30 degree of bank), in a T-40 simulator. Their study supported the Lyons, et. al. study in showing the feasibility of the concept, but concluded that such restricted acoustic cueing (relying on intensity differences) was problematic due to system or individual channelized biases.

Gillingham (1992) reported on the use of a modified version of the AOI in a flight test involving a Beach Queen Air. He found that pilots were able to better control bank angle with the AOI than with no information (blindfolded), in a manner that was statistically the same as with visual displays. He also reported that the auditory display of vertical velocity (through a perceived pitch change based on the Shepard Illusion) was not effective, primarily because vertical velocity is not a control parameter, and recommended that inclusion of aircraft pitch information would be more useful.

The Auditory HUD developed for the present study is depicted in Figure 8. A single localized auditory cue was presented. The vertical location of the cue provided a command cue associated with the pitch of the aircraft. For example, a cue that was 15 degrees up from the horizon indicated that the pilot needed to bring the aircraft nose up 15 degrees to be level. The horizontal location of the cue provided a command cue associated with the roll of the aircraft. A cue that was 45 degrees to the right of center indicated that the pilot need to bring the right wing up 45 degrees to be level. Therefore, both a pitch and roll indication were provided through a single cue (earlier studies indicating that the use of multiple cues would be too demanding.) The characteristics of the cue were presented as discussed below. The cues were always referenced to what the pilot would need to do to become level, similar to cues provided in a visual HUD. In general, it was hypothesized that the presence of the three dimensional auditory cue corresponding to pitch and roll would enhance subject awareness of aircraft attitude and corresponding performance in visually demanding flight tasks.

To test this concept, a study was conducted to examine the utility of the Auditory HUD for augmenting subject awareness of aircraft attitude during a normal flight task. In addition to testing the Auditory HUD against a control (visual only) display condition, further exploration of cue characteristics for this type of display was conducted. The first study showed a benefit in vertical localization performance due to the use of a reference tone, a variable tone and a graduated tone. These tones were therefore examined in this

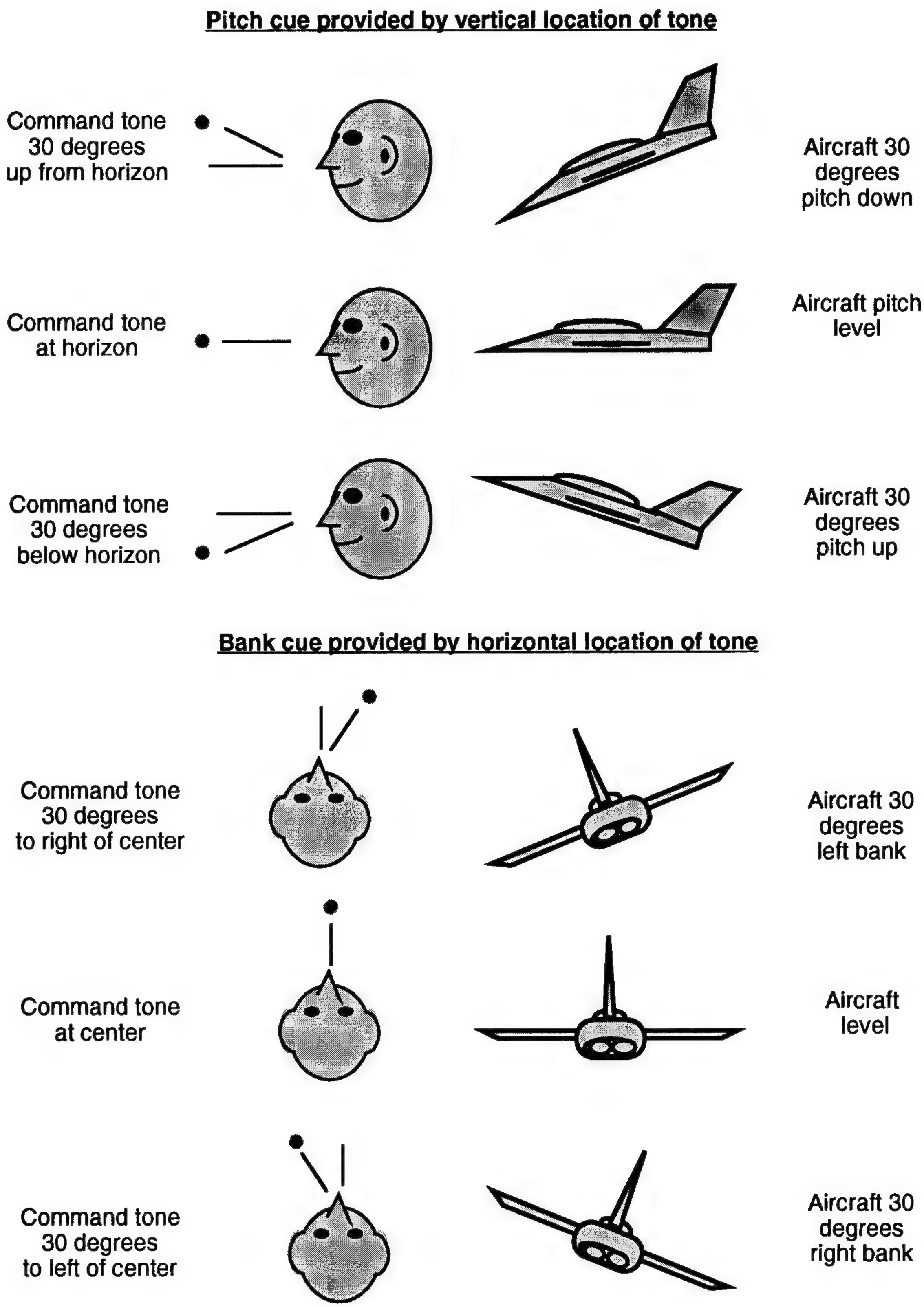

Figure 8. Auditory HUD

study within the context of the Auditory HUD concept. However, as the first study also showed some trade-offs in horizontal localization performance and response time with these cues, a single pure tone was again examined, providing a comparison point for the other cues. This was felt to be needed as the Auditory HUD required a much more complex discrimination within the context of other dynamic tasks (whereas in the first study only simple location judgments were required). In addition to this, broadband cues were examined as compared to the single frequency tones used in the first study since prior research has indicated that localization performance is better in the presence of broadband frequencies. Finally, the use of a continuous tone (which would provide more relative movement information, but which pilots had indicated might be too distracting) was examined, in comparison to a discrete tone which sounded every 3 seconds.

Methodology

Experimental Design - In all conditions, subjects performed a visual search task and a simulated flight task with visual displays as shown in Figure 9. Supplemental auditory cues were also provided in some conditions using the Auditory HUD display described above. The characteristics of the presented tones were varied as the independent variable. Eight conditions were explored:

(1) Visual Displays Only - Only the visual displays were present. No supplemental auditory cues were provided (control condition).

(2) Single Pure Tone - The cue provided through the Auditory HUD was a pure tone at a fixed frequency of 500 Hz. The tone was presented every three seconds with a duration of 900 ms.

(3) Single Broadband Tone - The cue provided through the Auditory HUD was a broadband tone which incorporated frequencies between 5000 Hz and 8000 Hz. The tone was presented every three seconds with a duration of 900 ms.

(4) Single Variable Broadband Tone- The cue provided through the Auditory HUD was a broadband tone (centered at 5000 to 8000 Hz). Tones at higher elevations were

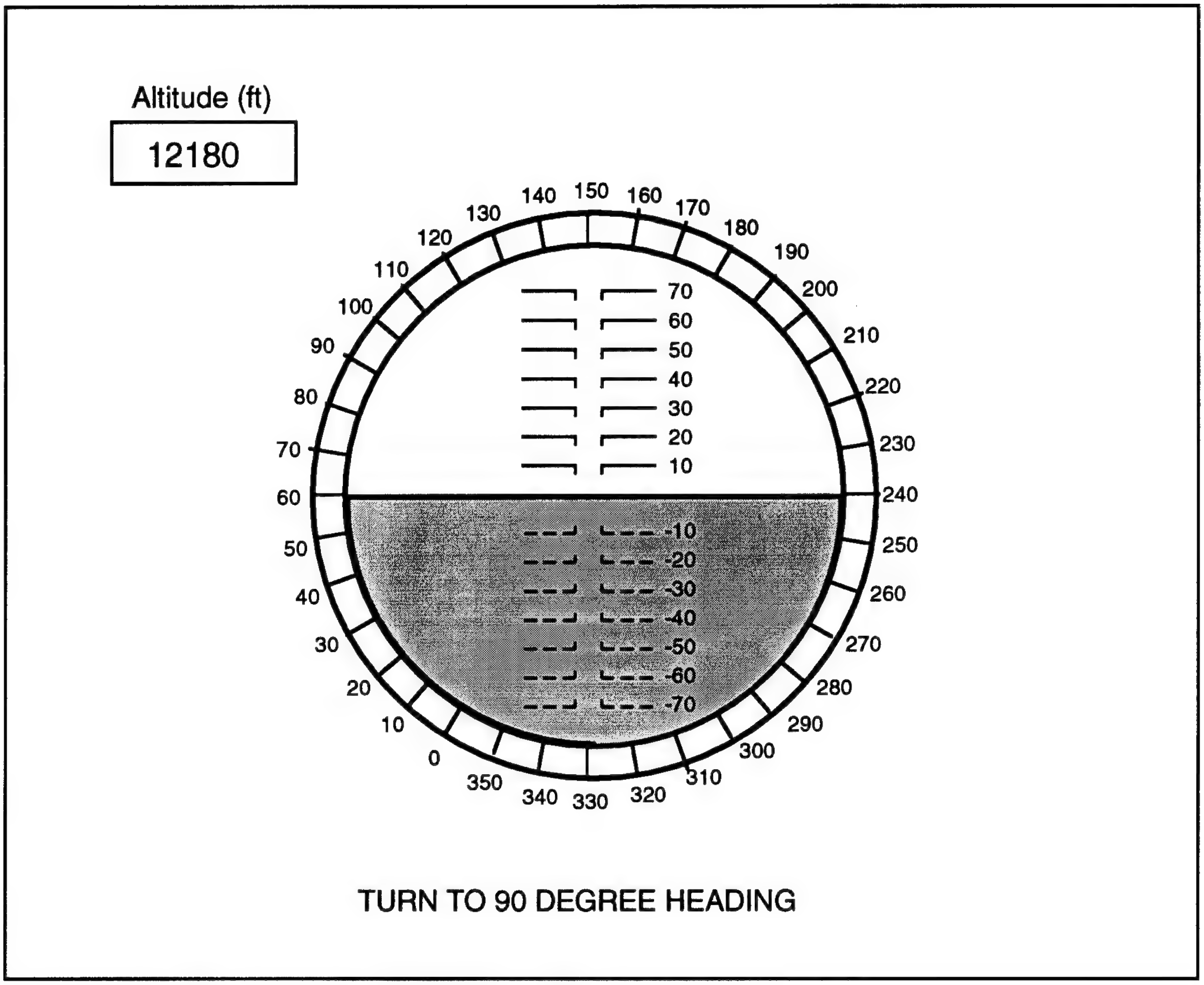

Figure 9. Aircraft flight path task display

presented with progressively higher frequencies (centered at frequencies ranging between 6800 and 9800 Hz) and tones at lower elevations were presented with progressively lower frequencies (centered at frequencies ranging between 3200 and 6200 Hz). The tone was presented every three seconds with a duration of 500 ms.

(5) Variable Reference Broadband Tone - The cue provided through the Auditory HUD consisted of a pair of broadband tones. The first tone indicated the location of the auditory HUD command cue. It was immediately followed by a second tone presented at 0 degrees elevation (at the same designated azimuth) to serve as an anchoring reference point. Tones at higher elevations were presented with progressively higher frequencies and tones at lower elevations were presented with progressively lower frequencies. The pair of tones was presented every three seconds with a duration of 500 ms each.

(6) Variable Graduated Broadband Tone - The cue provided through the Auditory HUD consisted of a series of broadband tones. The first tone indicated the location of the auditory HUD command cue. Succeeding cues were presented at five degree increments in elevation until 0 degrees elevation was reached. Tones at higher elevations were presented with progressively higher frequencies and tones at lower elevations were presented with progressively lower frequencies. The set of tones was presented every three seconds with a duration of 120 ms each.

(7) Continuous Broadband Tone - The cue provided through the Auditory HUD was a broadband tone centered at frequencies between 5000 and 8000 Hz. The tone was presented continuously with only a 50 ms break every 2 seconds.

(8) Continuous Variable Broadband Tone - The cue provided through the Auditory HUD was a broadband tone. Tones at higher elevations were presented with progressively higher frequencies and tones at lower elevations were presented with progressively lower frequencies. The tone was presented continuously with only a 50 ms break every 2 seconds.

All subjects were presented with all 8 possible tone type conditions. Conditions were administered in random order. The dependent measures for each subject's performance were time to reach the commanded altitude or heading, mean deviation from commanded flight path, time to respond to secondary task, and situation awareness of aircraft parameters.

Subjects - Eleven experienced male pilots from Reese Air Force Base participated in this investigation on a strictly voluntary basis in accordance with the standards of the Human Subjects Use Committee at Texas Tech University. All subjects reported normal hearing. Pilot subjects' mean age was 31.9 years and mean years of flight experience was 7.8. Nine subjects were fighter pilots (T-38 instructors) and two subjects were transport pilots (T-1 instructors).

Tasks - (1) Flight path task - Subjects were provided with a simulated HUD attitude display providing aircraft pitch and roll information, a compass, and digital altitude information (as shown in Figure 9). They were asked to follow flight path instructions which were visually displayed on the top half of the screen. Instructions provided command headings and altitudes which changed at periodic intervals. The subjects' task was to adhere to the command headings and altitudes as closely as possible. Once arriving at a designated altitude and heading, the pilot was required to maintain that position until a new command appeared on the screen.

(2) Visual search task - Subjects were required to concurrently perform a visual search task (Jensen, Adrion, Maresh, & Weinert, 1987). A second computer monitor placed adjacent to the first monitor contained 25 rows of 80 small red dots on a black background. Periodically the color of one of the dots randomly changed in color from red to magenta. The subject's task was to press a key on the keyboard as soon as a change in color was detected. Once a key was pressed, the dot returned to its original color and the process was repeated.

Procedure - Subjects were provided a brief description of the tone they would hear and the two tasks they were required to perform. They were then allowed one practice session performing the two tasks with the auditory tone. The practice session lasted approximately five minutes. Upon completion of the practice session, subjects were asked to perform the flight task and the secondary visual search task concurrently. Each trial for a given auditory tone condition lasted five minutes.

The Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988; Endsley, 1990; Endsley, 1995) was used to test for subject awareness of key aircraft parameters during the study. At four random times during the trial, the computer simulation was frozen and the screens for both tasks were blanked. At that time, subjects were asked to fill out a questionnaire which tested their knowledge of the aircraft's current altitude, heading, pitch and bank angle. Following completion of the questionnaire, subjects returned to the simulated flight tasks. This process was completed for each of the test conditions. A subjective questionnaire was completed by each subject after completing all test conditions.

Apparatus - The tones were generated through the Focal Point Three-Dimensional Audio System by Gehring Research on a 486 IBM compatible computer, as reported in Study One. Standard headphones were used to deliver the generated tones. Two 486 IBM compatible computers with 13" color monitors were used to present the two tasks.

Results

Flight Path Error - Root mean square (RMS) error was calculated for adherence to command heading and command altitude in the flight path task. An ANOVA was performed on altitude RMS error, as shown in Table 4. Subject, flight path command and auditory tone condition were all significant indicators of altitude RMS error at the $\alpha = .05$ level.

Table 4. Analysis of Variance: Altitude RMS Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	6397171	7	913881	3.128	0.003
Command	14636200	7	2090891	7.157	0.000
Subject	18525900	10	1852587	6.341	0.000
Error	148416000	508	292157		

Tukey tests were performed to examine the locus of the differences in auditory tone conditions, shown in Figure 10. The single broadband tone, single variable broadband tone, continuous variable broadband tone and the visual only (control) conditions were relatively the same, indicating no added benefit for these types of auditory cues when compared to the no audio control condition. The continuous broadband tone and the variable reference broadband tone produced slightly higher RMS error scores, indicating that tracking performance was worse when these cues were present. The graduated variable broadband tone and the single pure tone produced slightly lower RMS error scores, indicating that tracking performance was improved with these two types of cues.

Significant differences were also observed in relation to which of eight command altitudes had been given, which is as would be expected since the amount of change required to reach each altitude would be different, and between the eleven subjects. Significant variability in subject performance in auditory localization tasks is also quite common.

An ANOVA was performed on heading RMS error, as shown in Table 5. While RMS error varied significantly on the basis of which of eight command headings had been given, it did not vary as a function of subject or auditory tone condition at the $\alpha = .05$ level.

Visual Search Task Response Time - Reaction time in the visual search task was analyzed with an ANOVA, as shown in Table 6. Reaction time varied significantly as a function of subject, but was not significantly affected by the auditory tone condition or

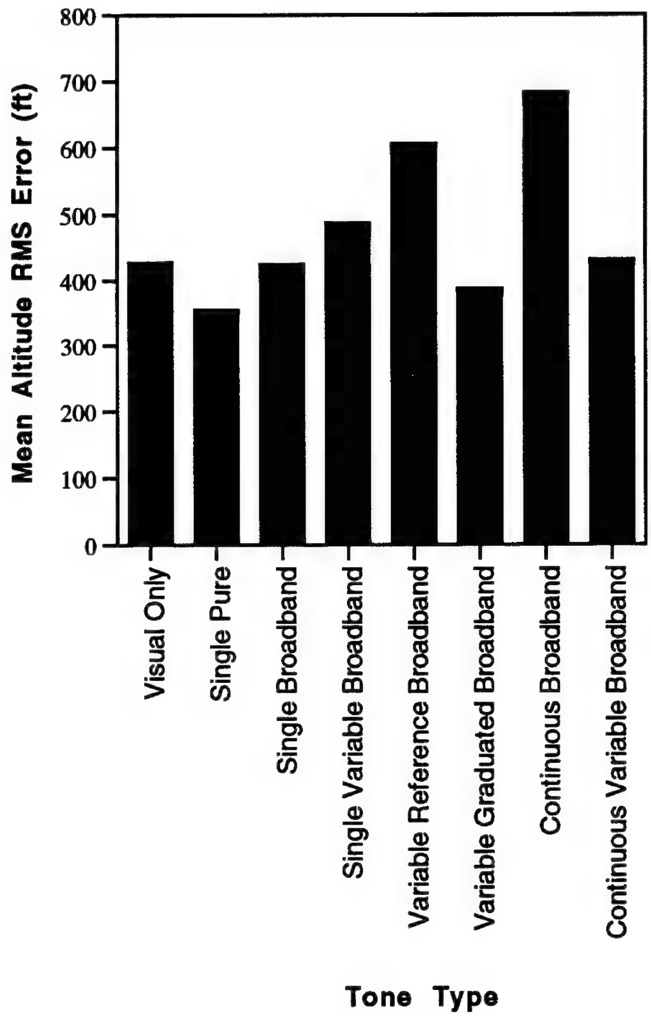

Figure 10. Mean altitude RMS error by tone type

command given. An analysis of the trend in reaction time (Figure 11) showed a slightly faster response time in the single pure tone, variable graduated broadband tone, and continuous variable broadband tone conditions, generally supporting the findings of the altitude RMS error scores and indicating that a trade-off between primary and secondary tasks was not occurring as a function of the auditory cues.

Table 5. Analysis of Variance: Heading RMS Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	2132	7	304	.545	0.800
Command	15098	7	2157	3.859	0.000
Subject	4555	10	455	.815	0.614
Error	284482	509	559		

Table 6. Analysis of Variance: Visual Search Reaction Time

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	7.08	7	1.01	.356	0.924
Command	26.86	7	3.84	1.352	0.243
Subject	167.07	10	16.71	5.88	0.000
Error	170.32	60	2.839		

SAGAT Scores - Subject perceptions of current aircraft altitude, heading, bank, and pitch at the time of each simulation freeze were compared to actual values and error scores calculated. Each response was scored as correct or incorrect based on established aircraft tolerance levels. ANOVAs were calculated for each error score (adjusted by an arcsine transformation to account for non-normality in binomial data), shown in Table 7. None of the error scores was significantly impacted by the auditory tone condition at the $\alpha = .05$ level.

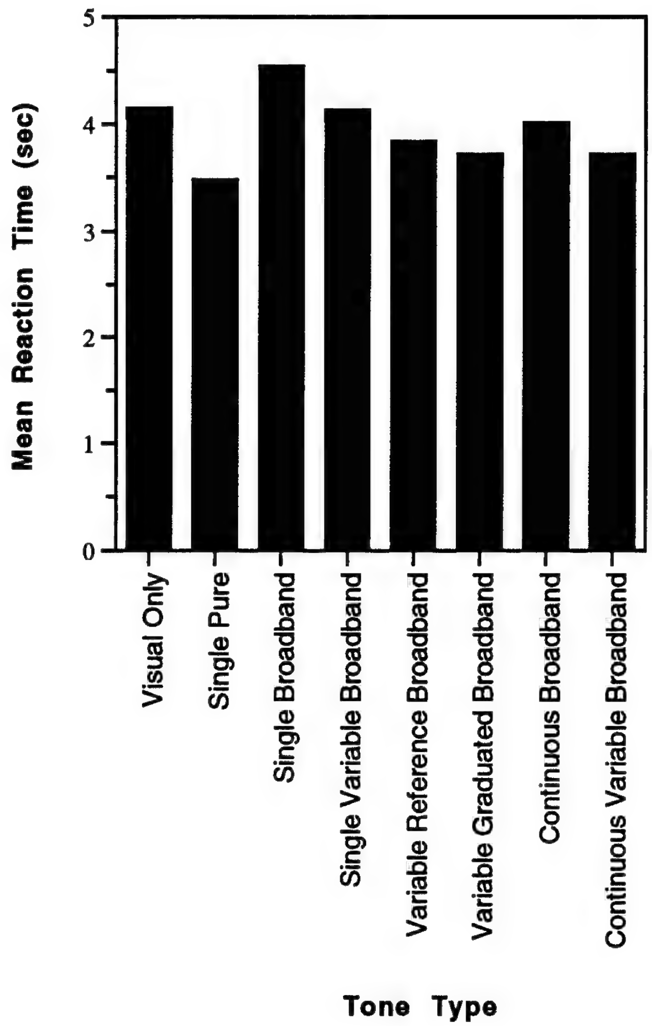

Figure 11. Mean visual search task reaction time

Table 7. Analyses of Variance: SAGAT Responses

Altitude Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	.742	7	.106	.250	0.972
Command	6.878	7	.983	2.320	0.026
Subject	2.322	10	.232	.548	0.855
Error	117.319	277	.424		

Heading Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	1.721	7	.246	.475	0.852
Command	17.335	7	2.476	4.787	0.000
Subject	4.520	10	.452	.874	0.558
Error	140.716	272	.517		

Bank Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	1.448	7	.207	.446	0.872
Command	33.461	7	4.780	10.311	0.000
Subject	4.919	10	.492	1.061	0.393
Error	128.418	277	.464		

Pitch Error

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	.684	7	.098	.300	0.954
Command	19.590	7	2.799	8.589	0.000
Subject	3.552	10	.355	1.090	0.370
Error	90.253	277	.326		

Discussion & Conclusions

Subject performance in the flight task was significantly impacted by the presence of the auditory cues. This effect only occurred in relation to the management of aircraft altitude, however, and not for aircraft heading. This may be because the cues were more prevalent in their presentation of pitch information, or because subjects did not attend to the bank angles cues as much. It is of come concern that a benefit was only realized for some cues and a decrement in performance realized for others. The decrement most likely occurred for cues that were considered distracting or mentally demanding to process. The two cues that seemed to aid performance in this task were the pure tone condition and the graduated variable broadband tone. In previous testing, a graduated variable tone produced the best vertical localization performance (compared to all other cues), most likely due its ability to convey information through multi-dimensional channels. The pure tone had produced the worst localization performance in previous tests, however. None-the-less, subjects performed well with it in this test, possibly due to the fact that it would be fairly simple to process when performing other tasks.

While it was expected that the presence of the auditory cue might allow subjects to divert their attention to the secondary visual search task more often, the data did not support that this occurred, indicating that subjects continued to direct their attention across the two tasks in the same manner as with the visual display alone. It is somewhat positive that subjects had the best reaction time to the visual search task in the variable graduated broadband tone and single pure tone conditions (based on non-significant trends), confirming the results of the altitude RMS error analysis.

The SAGAT analyses did not show a significant effect of tone type. Thus, one cannot support better overall awareness of aircraft parameters with the auditory cues. The fact that task performance was better in some conditions indicates that subjects must have been able to use the cues, however, at least in some indirect way. It may be that they were not able to verbalize this knowledge, however.

Overall, while the results of this study are somewhat perplexing (in that the pattern of which cues were beneficial is difficult to interpret), it appears that the use of the Auditory HUD may have some benefit in complex flight tasks. The greatest concern will be to select cues that can be easily processed by subjects under these conditions.

STUDY THREE

In order to further test the utility of the Auditory HUD, a third study was conducted to examine whether it would provide assistance in a recovery from unusual attitude task. The Auditory HUD was implemented to be always present, even when the aircraft was being flown to its unusual attitude (with no visual information presented), as research by Gillingham (1992) had found auditory cues may prevent disorientation by providing a useful reference when visual information is absent. It was expected that the presence of the Auditory HUD could be used by subjects to aid in recovery from an unusual attitude, thus indicating potential benefit in preserving attitude awareness. It was furthermore expected that if a benefit was present due to the Auditory HUD, it would be more pronounced with inexperienced pilots who typically have more trouble with disorientation accidents, possibly due to the relatively higher workload experienced by them. In this study, the two tone types producing the best performance in Study Two, a single pure tone and a graduated variable broadband tone, were selected for implementation with the Auditory HUD concept.

Methodology

Experimental Design - Two independent variables were present in this study: Auditory Tone Type and Subject Type.

(1) Auditory Tone Type

(a) Visual Displays Only - Subjects performed the task using only the aircraft instruments provided by the simulator. No out of window displays or supplemental auditory cues were provided (control condition).

(b) Single Pure Tone- The cue provided through the Auditory HUD was a pure tone at a fixed frequency of 500 Hz. The tone was presented every three seconds with a duration of 900 ms.

(c) Graduated Variable Broadband Tone- The cue provided through the Auditory HUD consisted of a series of broadband tones. The first tone indicated the location of the auditory HUD command cue. Succeeding cues were presented at five degree increments in elevation until 0 degrees elevation was reached. Tones at higher elevations were presented with progressively higher frequencies and tones at lower elevations were presented with progressively lower frequencies. The set of tones was presented every three seconds with a duration of 120 ms each.

(2) Subject Type

(a) Instructor Pilots - Six experienced T-38 pilots,

(b) Student Pilots - Six inexperienced pilots undergoing training in the T-38. These subjects had completed basic instrument flight training and recovery from unusual attitude maneuvers and were familiar with the training simulator.

All subjects were presented with all 3 possible conditions. Conditions were administered in random order. The dependent measures for each subject's performance were time to return to 0 degrees pitch and 0 degrees roll from the given unusual attitude.

Subjects - Twelve male pilots from Reese Air Force Base participated in this investigation on a strictly voluntary basis in accordance with the standards of the Human Subjects Use Committee at Texas Tech University. All subjects reported normal hearing. Six subjects were instructor pilots and six subjects were student pilots. The student pilot subjects' mean age was 25.8 and mean years of flight experience was 2.9 years. The instructor pilot subjects' mean age was 30.5 years and mean years of flight experience was 8.7 years. Eleven of the subjects reported they had previously experienced spatial disorientation.

Task - Subjects were provided a brief description of the tone they would hear and the task they were required to perform. They were then allowed a brief practice session in which they recovered from six unusual attitudes. Upon completion of the practice session, subjects were then asked to fly the plane back to level from six different unusual attitudes as rapidly as possible. Upon leveling the aircraft (0 degrees pitch and bank), the pilot was instructed to verbally say "level" and to maintain that position until a new unusual attitude was provided. Visual displays were covered while the aircraft was being maneuvered to its unusual attitude and were uncovered at the start of each trial. The Auditory HUD was displayed throughout while the aircraft was maneuvered to the unusual attitude and while the subject was performing the recovery maneuver (in those two conditions). Each condition lasted approximately 10 minutes.

Apparatus - A T-38 training simulator at Reese Air Force Base was used for the test. The tones were generated through the Focal Point Three-Dimensional Audio System by Gehring Research on two 486 IBM compatible computers, as in Study Two. Standard headphones were used to deliver the generated tones.

Results

The data were analyzed as a two factor experiment: (1) Auditory Tone Type (visual only, single pure, graduated variable broadband) and (2) Subject Type (instructor pilot, student pilot). The effect of each variable on subject response time was examined. A total of 216 trials were presented across the 3 conditions and 12 subjects.

Results of an ANOVA for response time (Table 8) showed no significant effect of auditory tone condition at the $\alpha = .05$ level, as shown in Figure 12. Although instructor pilots' mean response time (8.5 sec) was slightly faster than student pilots' mean response time (14.1 sec), this was not statistically significant. There was a significant effect of starting condition (the unusual attitude) used for each trial, as would be expected.

An examination of accuracy was also conducted. The amount of error (in pitch and in roll) at the time the subject said "level" was also examined. While there was a difference

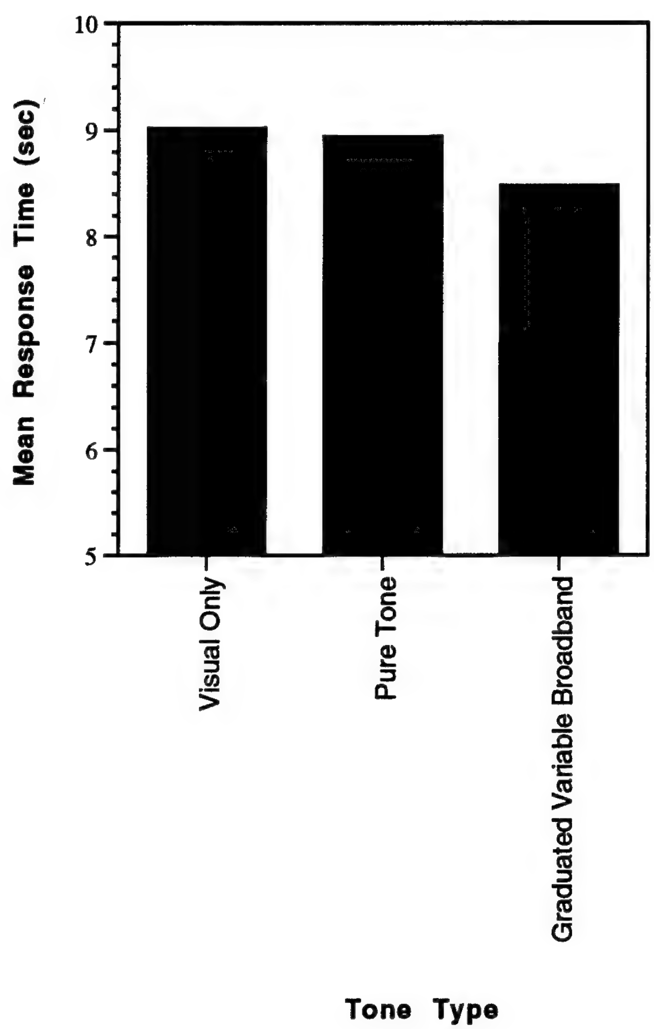

Figure 12. Mean response time by tone type

Table 8. Analysis of Variance: Response Time

Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	14.00	2	7.00	.353	0.703
Subject Type	33.43	1	33.43	1.684	0.196
Starting Attitude	1861.55	17	109.50	5.52	0.000
Error	3771.95	190	19.85		

between subject types, there was no significant difference between auditory tone conditions or starting condition on accuracy at $\alpha = .05$, as shown in Table 9. Instructor pilots had slightly more error in roll (approximately 3 degrees) and student pilots had slightly more error in pitch (approximately 1 degree) at the time they stated that they were level.

Table 9. Analysis of Variance: Response Accuracy

Pitch Error at Level					
Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	6.92	2	3.46	.707	0.494
Subject Type	24.62	1	24.62	5.031	0.026
Starting Attitude	58.73	17	3.45	.706	0.795
Error	934.72	191	4.89		
Roll Error at Level					
Source	Sum-of-Squares	df	Mean-Square	F	p
Tone Type	27.27	2	13.64	.568	0.567
Subject Type	352.39	1	352.39	14.688	0.000
Starting Attitude	153.72	17	9.04	.377	0.989
Error	4582.52	191	23.99		

Subjectively, subjects indicated that the felt supplemental information on attitude through the auditory signals was a little useful (9 subjects), or somewhat useful (3 subjects). They reported that they would like the signals to be presented on request (4 subjects) or in potentially disorienting conditions (8 subjects).

Discussion

While the auditory cues examined could be successfully localized and provided some improvement in the dual task flight path study, they did not improve performance in this recovery from unusual attitude task utilizing a high fidelity aircraft simulator. As the auditory cues were only supplemental, it was entirely possible to perform the task while completely ignoring the auditory cue. As all prior training on this task is with visual flight displays, this is most likely how subjects performed this task. Since subjects could process the information and perform the task visually, no benefit from the auditory information was realized. (There was no attempt to conduct the task with only the auditory display, as it was felt that localization accuracy with the auditory cues was not good enough to allow this to be feasible.)

Recommendations and Conclusions

Subjective questionnaires on the use of audio tones as a means of recovering or preventing spatial disorientation indicated that subjects felt tones would be useful as a whole. Subjects did however prefer to have the supplementary tones present only in potentially disorienting conditions and/or on request. Most subjects felt that a longer practice session would have been useful to better utilize the auditory cues correctly. Subjects suggested possible problems with the tones, including: interference with other communications, difficulty of interpretation, and too much to think about in a fighter aircraft. Subjects recommended the use of a steady tone instead of a graduated tone when level and a faster tone to indicate pitch up and a slower tone to indicate pitch down. All subjects recommended a longer training session to become accustomed to the tone.

CONCLUSIONS

These studies show that while the presentation of aircraft attitude through auditory cues may be possible, considerable work is still needed to develop cues that provide usable information to pilots. Previous studies (Gillingham, 1992; Neubauer, et. al., 1992) showed that pilots did better in performing flight tasks with auditory cues than with no displays at all. In this research, an effort was made to determine if a benefit could be found for using localizable auditory cues as a supplement to traditional visual displays. While some advantage was found for the use of supplemental three-dimensional auditory cues in the flight path tracking task in Study 2, no added benefit was found in the recovery from unusual attitude task in Study 3.

Several issues bear consideration. First, it may be that more of an advantage could be found with different cues than those used here. While Study 1 served to create cues that could be more readily discerned in the vertical dimension (an issue which has not received much prior research attention), there is no guarantee that other cues might not be better than the ones used in this study. In addition, the localizability of the cues would probably be significantly enhanced with individualized head related transfer functions (HRTFs), which were not used in these studies as non-individualized HRTFs would probably be more readily implemented in cockpits in mass. It is recommended that the technology used to produce the localized cues may be improved through continued research as well. Subject localization accuracy was considerably poorer than free-field listening, even in the horizontal dimension.

Even though the subjects in this study did not find added benefit from the displays in recovering from unusual attitudes, it is reassuring that performance did not degrade with the use of the auditory cues showing that they were not overly distracting. Further research should be conducted to test the Auditory HUD under conditions of actual spatial disorientation. It may be that under normal conditions, pilots need no assistance with the

well trained recovery task, but that under disorientation the added auditory cues may provide a substantial benefit to pilots with disrupted visual and vestibular systems.

Subjective information from the pilots who served as subjects in this study indicates that they almost all saw at least some benefit from the use of three-dimensional auditory cues in the cockpit, however, most had concerns about how it would be implemented. As there can be a great deal of auditory noise, other signals and voice communications present in the cockpit, avoiding auditory overload was a concern. Most pilots favored an implementation strategy that would allow them to activate the cues only when needed (either automatically or at the pilot's discretion). Almost all felt that much more practice was needed to allow the cues to become easier to process.

Overall, this research served to develop three dimensional auditory cues that could be localized reasonably well in both the vertical and horizontal dimensions. These cues are particularly needed, as vertical localization provides a natural analog to aircraft attitude and coding in this dimension serves to allow more information to be conveyed to the pilot with a single signal. An Auditory HUD was developed for conveying aircraft pitch and roll using a single auditory cue that was usable by pilots in a flight path tracking task. The Auditory HUD needs further investigation to refine the cue characteristics used to best convey cue location to a listener. In addition, further research is needed to test the ability of subjects to localize auditory signals under conditions of spatial disorientation, and, in particular, the ability of pilots to use the Auditory HUD under such conditions.

ACKNOWLEDGMENTS

This research was conducted under Grant number F49620-94-1-0114 from the Air Force Office of Scientific Research, with the support and assistance of Lt. Col. Daniel Collins, grant monitor. We also thank Col. Roger Brady, Capt. Greg Garrett, Mr. Bill Duke and the pilots at Reese Air Force Base for their support and assistance in the conduct of this research.

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